Subspace Models for Acoustic Unit Discovery

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- Evaluations

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- Hierarchical Subspace HMM

Conclusion

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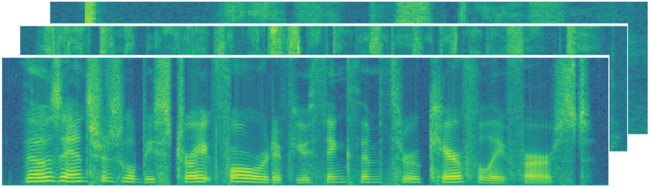
Definition of the task

- Audio recordings without labels
- Inventory of phone-like units (we call them “acoustic units”)
- Segmentation and labelling



Learning like a baby

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Documenting endangered languages

- Language diversity is diminishing world wide
  - Speech technologies are only available for a few languages
  - Majority of languages are not written: main-stream ASR is not applicable
- an accurate AUD system could:
  - help linguists to document languages
  - serve as a front-end of speech-technologies for non-written languages
- 2022-2032: The decade of Indigenous Languages

  ▸ UNESCO website

Computational model human learning

- The learning cognitive process of humans remains largely unknown:
  - the brain is very complex
  - "sensory learning" happens at a very early age, when the infants cannot communicate verbally
- Reverse engineering approach ("E. Dupoux. 2018") ▸ Link:
  - let's build model to learn speech in an unsupervised fashion
  - analyse it and derive the learning principle
  - pave the way to a more realistic artificial intelligence

Another type of machine learning

- The "always more data" approach raises concerns:
  - social/ethical problems: monopoly of ML technologies by LARGE data owner
  - ecological issues: more data implies more energy consumption
- AUD research implies data efficient models

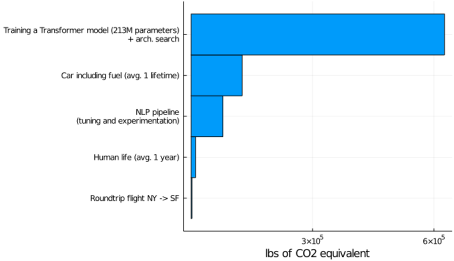

Figure: Energy consumption of training deep learning models. Source: Strubell *et al*, 2019 ▸ Link

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Brief history

- heuristic-based model: $\sim$ 1990 – 2005
- non-parametric Bayesian-based models: $\sim$ 2005 – 2020
- neural network-based models: $\sim$ 2015 – 2020

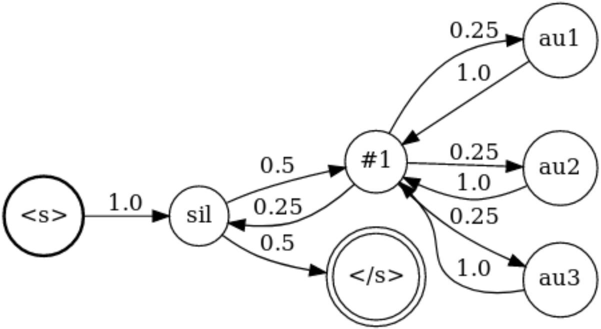
Neural network-based models

- VAE-HMM: Variational AutoEncoder with HMM/GMM prior over the latent space. ▸ Link
- Visually guided neural network: replace textual transcription by images ▸ Link
- VQ-VAE: AutoEncoder with discretized bottleneck ▸ Link

Non-parametric Bayesian-based models

- Non-parametric model for word segmentation ▸ Link 1 ▸ Link 2
- Dirichlet-Process HMM (2012) ▸ Link
- Dirichlet-Process HMM (Variational Bayes inference) (2016) ▸ Link

Dirichlet-Process HMM baseline



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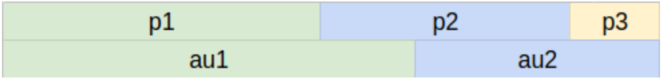
Metrics



p1 p2 p3

au1 au2

- Clustering:
  - Normalized Mutual Information: $200 \frac{MI(X,Y)}{H(X)+H(Y)} \%$
  - Measures the statistical relation between the discovered units and the ground truth transcription
  - 100 % → one-to-one mapping between AU and phones
  - 0 % → AUs are completely uninformative
- Segmentation:
  - F-score: harmonic mean of segmentation precision and recall
  - ± 20 ms tolerance allowed

Experiments

- Data:
  - Mboshi (Congo Brazzaville) - 3-4 hours
  - Yoruba (West Africa - Nigeria) - 10 hours
  - English (TIMIT) - 4 hours
- Features:
  - traditional features: MFCCs + Δ + $\Delta\Delta$

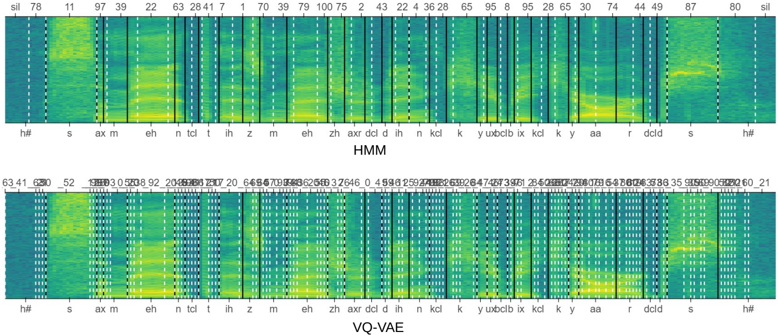
Results

- Adapted version of "Chorowski et al., 2019" ▸ Link
- Dirichlet Process HMM (VB inference) ▸ Link

Corpus	System	NMI	F-Score	# units
English	VQ-VAE	29.73	38.59	100
English	HMM	**35.47**	**63.03**	95
Mboshi	VQ-VAE 64	26.85	20.22	100
Mboshi	HMM	**36.47**	**47.93**	94
Yoruba	VQ-VAE 64	29.36	7.74	100
Yoruba	HMM	**36.71**	**28.47**	95

Table: Comparison of the HMM vs the VQ-VAE baseline

Example



HMM

VQ-VAE

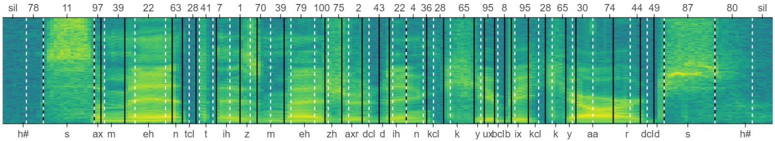
Results

- VQ-WAV2VEC “A. Baevski et al., 2020” trained on 960h of LibriSpeech (unsupervised) ▸ Link
- Dirichlet Process HMM (VB inference) ▸ Link

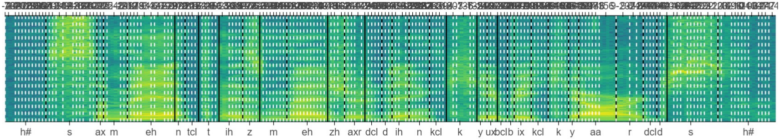
Corpus	System	NMI	F-Score	# units
English	VQ-WAV2VEC (Gumbel)	35.20	26.84	12008
English	VQ-WAV2VEC (K-mean)	34.06	25.64	20057
English	HMM	**35.47**	**63.03**	95

Table: Comparison of the HMM vs the VQ-VAE baseline

Example



HMM



VQ-WAV2VEC

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Motivations

- Infants do not learn from scratch (Kuhl *et al*, 1992 ▸ Link):
  - They have some innate sensitivity to human languages
  - With time, they become specialized to their native language
- Hypothesis/Design choice:
  - This innate sensitivity guide infants to learn the structure of speech
  - The AUD system should adapt and become language specific
- Proposal: we will use Bayesian Subspace Model techniques to implement these properties:
  - Subspace Hidden Markov Model (SHMM)
  - Hierarchical Subspace Hidden Markov Model (HSHMM)

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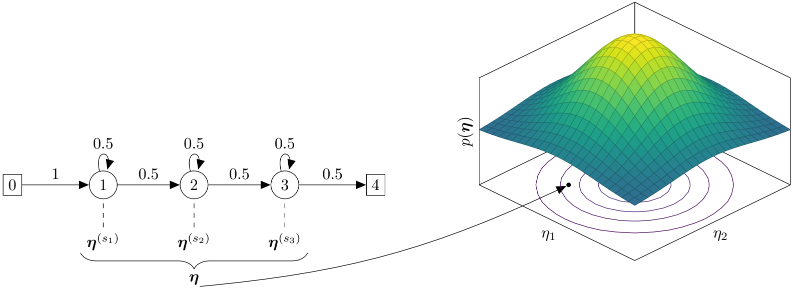
Learning an acoustic unit

$$p(\boldsymbol{\eta}|\mathbf{X}) = \frac{p(\mathbf{X}|\boldsymbol{\eta})p(\boldsymbol{\eta})}{p(\mathbf{X})} \tag{1}$$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η_1
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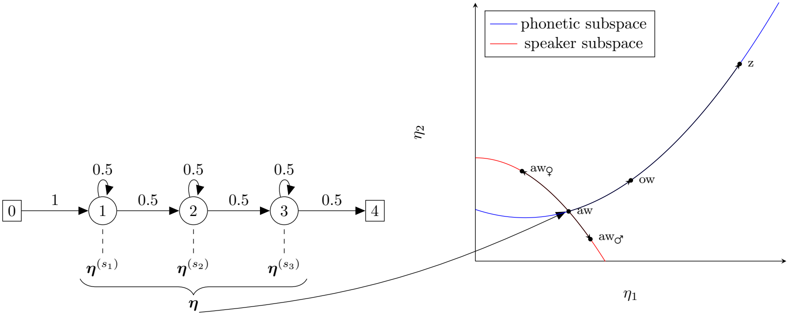
Phonetic Subspace



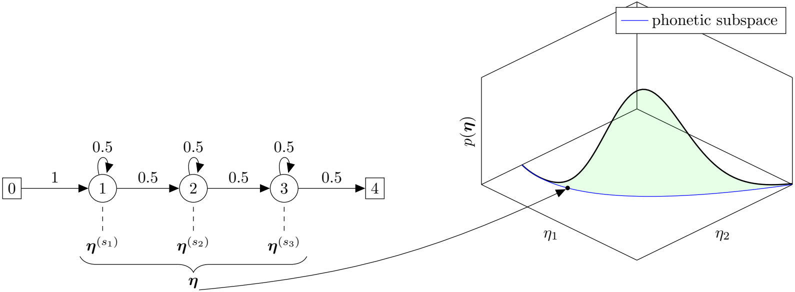
Prior over the the AU's parameters

- We want to design an educated prior over the AU's parameters : $p(\boldsymbol{\eta})$
-

$$\mathbf{h} \sim \mathcal{N}(\mathbf{0}, \mathbf{I}) \tag{2}$$

$$\boldsymbol{\eta} = f(\mathbf{Wh} + \mathbf{b}) \tag{3}$$

Subspace HMM



Inference I - Supervised learning

- We estimate the subspace parameters $\mathbf{W}, \mathbf{b}$ on annotated corpora
- Model is trained by optimizing the Evidence Lower-BOund (ELBO):

$$
\begin{aligned}
\mathcal{L} = &\langle \ln p(\mathbf{X}, |\mathbf{z}, \mathbf{W}, \mathbf{b}, \mathbf{h}_{1:T}) \rangle_q \\
&- \mathrm{D}_{\mathrm{KL}}(q(\mathbf{z})||p(\mathbf{z})) \\
&- \mathrm{D}_{\mathrm{KL}}(q(\mathbf{W})q(\mathbf{b}))||p(\mathbf{W})p(\mathbf{b})) \\
&- \mathrm{D}_{\mathrm{KL}}(q(\mathbf{h}_{1:T})||p(\mathbf{h}_{1:T}))
\end{aligned}
$$

- The training follows an Expectation-Maximization-like training:
  - E-step: Baum-Welch algorithm to estimate states' occupancy
  - M-step: No closed form solution, using re-parameterization trick.

Inference II - Unsupervised learning (AUD)

- The subspace parameters $\mathbf{W}, \mathbf{b}$ are fixed, we just learn the embeddings $\mathbf{h}$ on the target language
- Model is trained by optimizing the Evidence Lower-BOund (ELBO):

$$\begin{aligned}\mathcal{L} = &\langle \ln p(\mathbf{X}, |\mathbf{z}, \mathbf{W}, \mathbf{b}, \mathbf{h}_{1:T}) \rangle_q \\ &- \mathrm{D}_{\mathrm{KL}}(q(\mathbf{z}))||p(\mathbf{z})) \\ &- \mathrm{D}_{\mathrm{KL}}(q(\mathbf{h}_{1:T})||p(\mathbf{h}_{1:T}))\end{aligned}$$

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Illustration

▶ Link

Experiments

- Data:
  - Source languages (transcribed)
    - French, German, Polish, Spanish from Globalphone
    - 3-4 hours subsets of each language's training data
  - Target languages (untranscribed)
    - Mboshi (Congo Brazzaville) - 3-4 hours
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- Features:
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Results

Corpus	System	Training	NMI	F-Score
English	HMM	no	1.74	0.20
English	SHMM	no	20.83	58.94
Mboshi	HMM	no	1.65	0.02
Mboshi	SHMM	no	21.0	39.28
Yoruba	HMM	no	4.43	1.26
Yoruba	SHMM	no	26.1	27.45

Table: Comparison of the HMM vs the SHMM before training

Corpus	System	Training	NMI	F-Score
English	HMM	no	1.74	0.20
English	HMM	yes	35.47	63.03
English	SHMM	no	20.83	58.94
English	SHMM	yes	**39.66**	**75.92**
Mboshi	HMM	no	1.65	0.02
Mboshi	HMM	yes	36.47	47.93
Mboshi	SHMM	no	21.0	39.28
Mboshi	SHMM	yes	**38.42**	**57.26**
Yoruba	HMM	no	4.43	1.26
Yoruba	HMM	yes	35.27	28.83
Yoruba	SHMM	no	26.1	27.45
Yoruba	SHMM	yes	**37.56**	**36.64**

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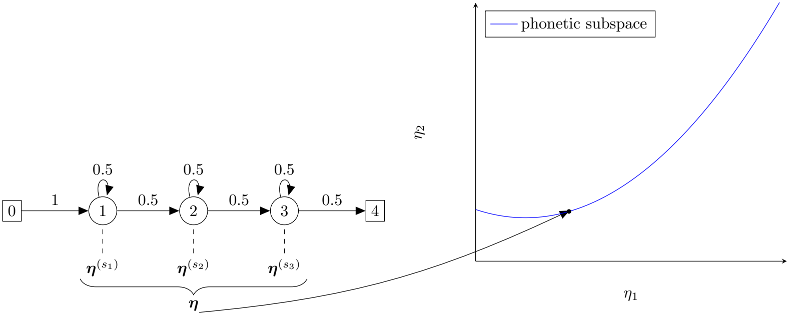
Revisiting the Phonetic Subspace

- We assume the subspace is known and fixed during AUD
- Subspace is the same for all the target languages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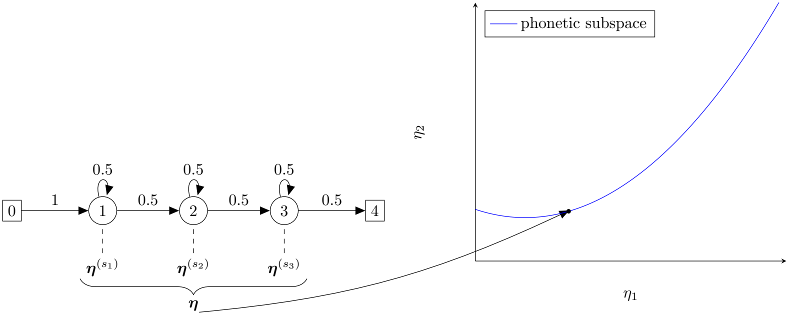
Revisiting the Phonetic Subspace

- We would like to adapt the subspace to make it language specific



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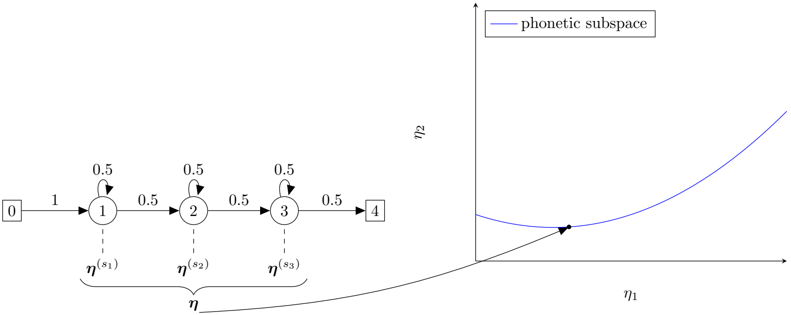

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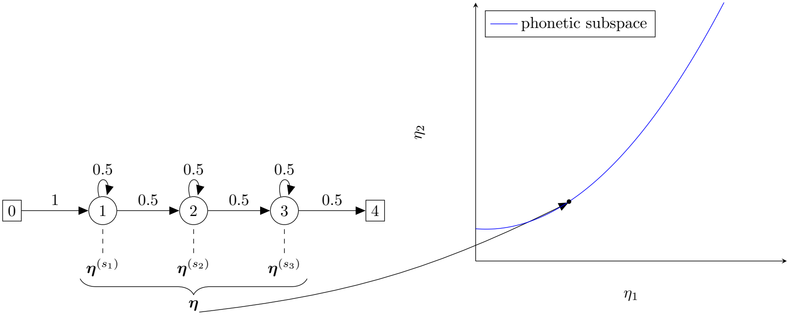

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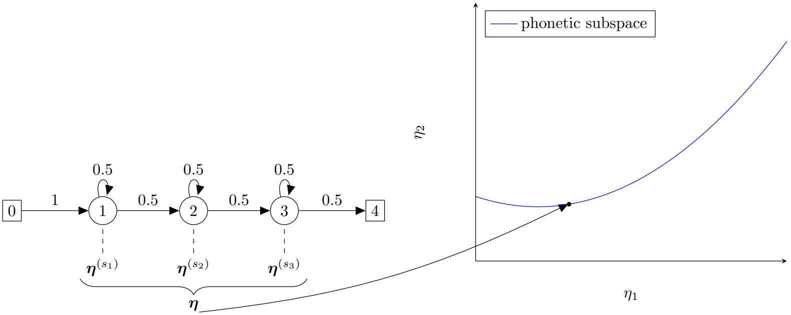
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$\boldsymbol{\eta}^{(s_3)}$
$\boldsymbol{\eta}$

Prior over the subspace

- We want to design an educated prior over all possible subspace: $p(\mathbf{W}, \mathbf{b})$
-

$$\boldsymbol{\alpha} \sim \mathcal{N}(\mathbf{0}, \mathbf{I}) \tag{4}$$

$$\mathbf{W} = \sum_{i=1}^{Q} \alpha_i \mathbf{M}_i \tag{5}$$

$$\mathbf{b} = \sum_{i=1}^{Q} \alpha_i \mathbf{m}_i \tag{6}$$

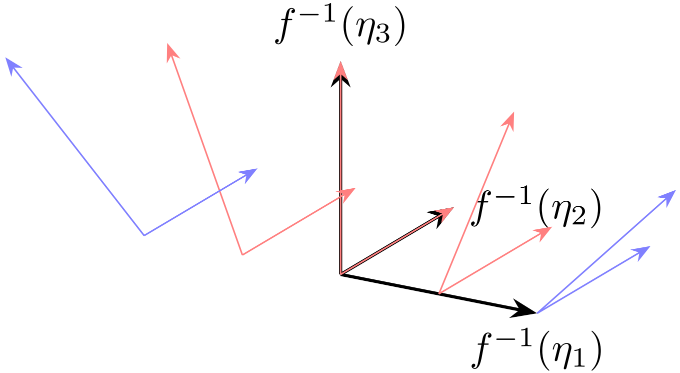
$$\mathbf{h} \sim \mathcal{N}(\mathbf{0}, \mathbf{I}) \tag{7}$$

$$\boldsymbol{\eta} = f(\mathbf{W}\mathbf{h} + \mathbf{b}) \tag{8}$$

Illustration

$$\boldsymbol{\alpha} = [\alpha_1, \alpha_2]^\top \tag{9}$$

$$\mathbf{W} = \alpha_1 \mathbf{M}_1 + \alpha_2 \mathbf{M}_2 \tag{10}$$



Inference I - Supervised learning

- We estimate the “hyper-subspace” parameters $\mathbf{M}, \mathbf{m}, \boldsymbol{\alpha}$ on annotated corpora
- Model is trained by optimizing the Evidence Lower-BOund (ELBO):

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&- \mathrm{D}_{\mathrm{KL}}(q(\mathbf{M}_{1:Q}) q(\mathbf{m}_{1:Q}) || p(\mathbf{M}_{1:Q}) p(\mathbf{m}_{1:Q})) \\
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Inference II - Unsupervised learning (AUD)

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Table: Comparison of the HMM, SHMM and HSHMM

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Mboshi	SHMM	38.42	57.26
Mboshi	SHMM (2)	35.50	51.28
Yoruba	HMM	35.27	28.83
Yoruba	SHMM	37.56	36.64
Yoruba	SHMM (2)	35.72	31.34

Table: Comparison of the HMM, SHMM and HSHMM

SHMM (2): the subspace is retrained on the target language.

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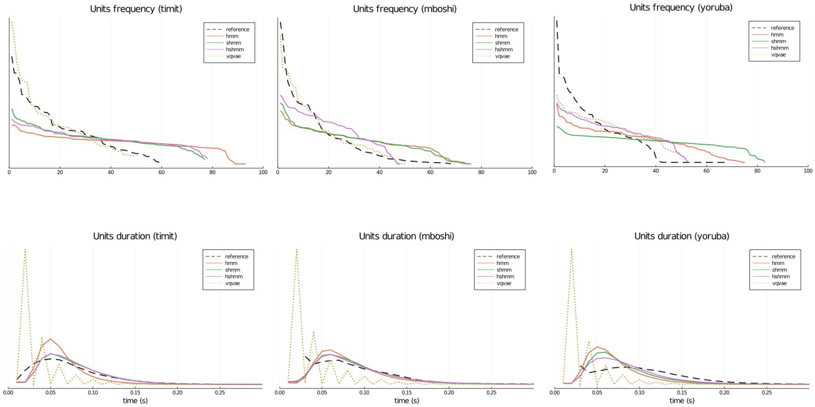
English	SHMM (2)	37.46	72.19
English	HSHMM	**40.56**	**78.32**
Mboshi	HMM	36.47	47.93
Mboshi	SHMM	38.42	57.26
Mboshi	SHMM (2)	35.50	51.28
Mboshi	HSHMM	**41.17**	**60.82**
Yoruba	HMM	35.27	28.83
Yoruba	SHMM	37.56	36.64
Yoruba	SHMM (2)	35.72	31.34
Yoruba	HSHMM	**37.88**	**38.44**

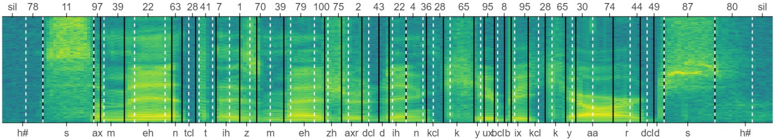
Table: Comparison of the HMM, SHMM and HSHMM

SHMM (2): the subspace is retrained on the target language.

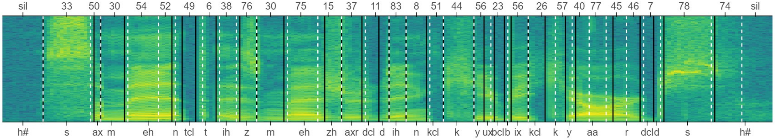
Some statistics



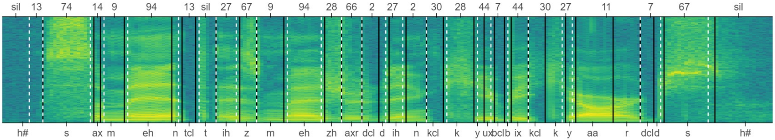
Example



HMM



SHMM



HSHMM

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Major approaches

Evaluations

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Motivations

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Hierarchical Subspace HMM

Conclusion

Summary

- We have proposed two new models for the task of Acoustic Unit Discovery:
  - Subspace Hidden Markov Model
  - Hierarchical Subspace Hidden Markov Model
- These models are inspired by how infants learn to speak
- They show strong improvement in terms of clustering and segmentation quality
- The concept of (hierarchical) subspace and can be extended to a large class of models
- To reproduce our experiments:

  `https://github.com/beer-asr`

Future Challenges

- AUD is not a solved problem!
- Model suffers from high variability of speech
- Two major problems:
  - Acoustic modeling: going beyond HMM
  - Language modeling: discovery words
- Towards the first system to learn speech as humans...

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Thank you for your attention.